ADAPTIVE FRONTAL STRUCTURE DESIGN TO ACHIEVE OPTIMAL DECELERATION PULSES

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ABSTRACT

To minimize the injury of car occupants during a frontal crash not only the restraint system must be optimized, but also the crash pulse generated by the vehicle structure. It is clear that a low velocity crash with full overlap requires less structure stiffness than a high velocity offset crash. Ideally for each serious crash situation the whole available deformation length must be used and all the impact energy must be absorbed without deforming the passenger compartment. For compatibility it is necessary to have a stiffer structure in case of a heavy opponent and a softer structure in case of a lighter opponent. This paper discusses possibilities to design an adaptive vehicle structure that can change the stiffness real time for optimal energy absorption in different crash situations. Besides that all the energy is absorbed it is also important to manage the intensity during the crash time, because the resulting crash pulse has a large influence on the injury level. Especially at high crash velocities a stiff structure in the first phase of the crash followed by a softer part is effective but difficult to realize with traditional structures. Therefore a comparison between several energy absorbing methods is made and friction is found as the best controllable way for adaptable energy absorption. In a proposed new concept design the right amount of energy could be absorbed by means of friction generated by hydraulic brakes on two rigid backwards moving beams. In case of an offset or oblique crash a mounted cable system moves the missed beam backwards. With this new intelligent design with interactive control, an optimal vehicle deceleration pulse can be possible for each crash velocity independent on the struck car position, yielding the lowest levels of the occupant injury criteria, also in case of compatibility problems.

INTRODUCTION

The improved frontal crashworthiness of cars necessitates totally new design concepts, which take into account that the majority of collisions occur with partial frontal overlap and under off-axis load directions against other cars with much larger or smaller masses and structure stiffnesses. Realistic crash tests with partial overlap have shown that conventional longitudinal structures are not capable of absorbing all the energy in the car front without deforming the passenger compartment. For improved frontal car safety it is necessary to design a structure that absorbs enough energy in each realistic crash situation. To protect the occupants, the passenger compartment should not be deformed and intrusion must be avoided too.

To prevent excessive deceleration levels, the available deformation distance in front of the passenger compartment must be used completely for a predetermined crash velocity. This implies that in a given vehicle concept the structure must have a specific stiffness. Normally, the two main longitudinal members have to absorb most of the crash energy with a progressive folding deformation of a steel column [1,2]. The main problem is that in real car collisions these two longitudinal members often are not loaded in a synchronous fashion. The majority of collisions occur with partial frontal overlap or with an oblique crash direction, in which only one longitudinal is loaded and often only a bending collapse occurs in stead of the much more energy absorbing progressive folding pattern. A design conflict is that the same amount of energy must be absorbed either with a single or with both longitudinals. This problem can not be solved by just definitively increasing the stiffness of the longitudinals in such a way that each longitudinal is capable of absorbing all of the energy. To absorb enough energy, a stiff longitudinal is needed for the offset crash or the oblique crash direction (also to have enough bending resistance) in which normally only one longitudinal is loaded. The same longitudinal must be suppler in case of a full overlap crash, since both longitudinals must not exceed the desired deceleration level.

To absorb all the kinetic energy, which is proportional with the square of the velocity, the deformable structure length must have a specific stiffness. This stiffness results in an average mean force, which multiplied with the deformation shortening gives the absorbed energy. For an acceptable injury level of the occupants, the total deceleration level must be as low as possible, using the maximum available deformation length without deforming the passenger compartment. This means that for example in a 64 km/h crash compared with a 32 km/h crash, a four times longer deformation distance is needed for the same deceleration level. Although the stiffness normally increases during the crash and at higher crash speeds there is made use of the stiff engine; the only way to generate an optimal crash pulse at different collision speeds is variable structure stiffness. After detection of the crash velocity, the optimal stiffness of the frontal structure should be realized.

The objective of the research project presented here was to design a concept structure that substitutes the conventional energy absorbing longitudinal members in a frontal vehicle structure and that yields optimized deceleration pulses for different crash velocities, overlap percentages and collision partners. If pre-crash sensing is used in future the system can be adjusted before the crash instead of during the crash. To this aim the structure must have a stiffness that can be varied in accordance with the specific crash situation.

Also the increasing trend of deployment of short front-end cars makes adaptive structures a must to overcome the impossible task of improving crashworthiness while shortening the front-end crash zone.

In the next section the problem is further analyzed, a summary is given on optimal crash pulses and finally a conceptual design will be presented which can fulfill the specifications of different deceleration levels for an optimal deceleration pulse in each crash situation.

ANALYSIS OF THE CRASHWORTHINESS PROBLEM

The novel design has to cope with the following four crashworthiness problems:

1. ***Crash position:*** in the case of a full overlap crash (both longitudinals and engine involved) as in the case of an offset or oblique crash (at 40 per cent overlap only one longitudinal directly involved) a similar amount of energy must be absorbed by the front structure.
2. ***Crash velocity:*** With a not much longer deformation length, much more energy must be absorbed at high crash velocities (resulting in less fatal injuries) and a lower injury level must be obtained at lower crash velocities.
3. ***Crash pulse:*** A deceleration pulse must be obtained which is optimal (lowest injury level) for the concerning relative collision speed and the chosen dummy restraint parameters.
4. ***Crash compatibility:*** The structure stiffness must also be optimized for the mass and stiffness of the struck object.

To minimize the injury of car occupants during a frontal crash, the car structure must generate a predetermined optimal deceleration pulse (specific curve) on the assumed undeformable passenger compartment to absorb all the kinetic energy. However, this optimal pulse is dependent on the final relative crash velocity and the occupant properties (for example initial distance occupant to airbag). The crash pulse must be independent on the struck car position. The absorbed energy must be dependent on the own accompanying mass (including passengers and luggage) and the relative final crash velocity, which is dependent on the original velocities of both crash partners and their mass relation (compatibility). This complex problem can only be solved if all the necessary parameter values in front of the crash are present by means of pre-crash sensing and a vehicle structure stiffness that can be regulated by an intelligent system immediately before and also during the crash (necessary if the crash parameters change or the deceleration has not the level as programmed). Especially the structure stiffness can influence the deceleration level and the absorbed energy within the available deformation length.

With this new intelligent design, an optimal vehicle deceleration curve must be possible for each crash velocity over the entire frontal collision spectrum, yielding the lowest levels of the occupant injury criteria, also in case of compatibility problems.

The compatibility of vehicles is an important issue. There could be adverse effects on vehicle fleet compatibility after structural changes. A vehicle which has a stiffer or more aggressive front structure for his own increased frontal safety could be more dangerous for another car, especially if that other car is involved in a side impact crash. Also the use of the same fixed deformable barrier in crash tests for light and heavy cars could lead to less compatibility in crashes between small and large cars. The amount of energy absorbed by the barrier is for a light car a larger proportion of the total crash energy as for a heavy car. To achieve a level of performance comparable to a small car, the front structure of the large car must be designed to crush more or to crush at a higher force level to absorb the additional energy. It is possible that a small car becomes softer because a lot of its energy was absorbed by the barrier. The increased crash velocity by Euro-NCAP from 56 km/h to 64 km/h has also a negative influence on the compatibility. This velocity increase yields a 30 per cent higher amount of crash energy. That means that for the same deformation length the force level and thus the stiffness of all cars has to grow with 30 per cent. This effect increases the absolute difference in force levels between light and heavy cars, which deteriorates the compatibility. Otherwise the test velocity must be higher as where collision statistics ask for, because for a comparable vehicle deformation as in a car to car crash the initial kinetic energy must be higher to compensate the absorbed energy in the barrier. Another interesting test for the compatibility problem is a test with a moving deformable barrier. Such a test simulates much better collisions between cars and could improve the fleet compatibility. In this case the smaller vehicle is subjected to a harsher crash environment due to the higher energy absorption and a higher velocity change yielding a stiffer structure. On the other hand the large car would be subjected to a less severe crash environment in terms of velocity change, so a softer front structure gives a temperate crash pulse.

OPTIMAL DECELERATION PULSES

An occupant is primarily protected by the restraint system, so an optimal vehicle crash pulse must always be defined in combination with the restraint system characteristics. For structural adaptivity much effort is needed in finding the properties of a well-tuned seatbelt and airbag system combined with a proper crash pulse shape. For an adaptive frontal stiffness system an optimized set of restraint system and crash pulse parameters should be defined for all types of frontal collisions. From previous research [3] it is known that a traditional deceleration curve with an increasing deceleration level, from the beginning with a relatively soft structure to the end of the crash with a high force level, is far from optimal. For a low crash velocity a constant crash pulse is ideal while for higher crash velocities a high-low-high crash pulse is optimal. An active control of the structural response is necessary in order to minimize restraint system loads in low speed impacts and to create high-low-high pulses for higher crash velocities.

Researchers Witteman [3], Motozawa and Kamei [4] studied the possibility of reducing occupant injury severity without increasing vehicle deformation by actively controlling the vehicle deceleration in a crash. The influence of the change in vehicle deceleration with time (the deceleration curve) on occupant injuries in crashes has been studied by modifying the deceleration curve of an actual vehicle and optimizing it in order to reduce occupant injury by using the sensitivity analysis method applied to dummy simulations.

Witteman [3] gave a method to calculate an overall severity index based on bio-mechanical injury criteria. An integrated numerical model of dummy and car interior was described with corresponding restraint parameters yielding the lowest overall severity index (OSI). With an ideal not deforming passenger compartment, it is acceptable to use an uncoupled model of the dummy and the frontal deforming structure. A common method is, to predefine a deceleration pulse as input on the passenger cage. With the aid of this interior model, variations of the deceleration pulse are compared on basis of the OSI, and an optimal pulse is obtained for several crash velocities. The conclusions are comparable with Brantman [5] that the pulse can be described by three phases, ensuring minimal risk for the occupants:

1. <u>Crash initiation phase.</u> In this phase, the sensor triggering for the belt pretensioners and airbags must take place. For optimal sensor triggering, the front-end of the car should be sufficient stiff to generate within a short time interval a velocity change that lies above the triggering value. The occupants are not directly connected with the car, because they are not yet captured by the restraint systems, so the deceleration can be high without causing unacceptable injury. Loss of valuable deformation shortening during a still high velocity is reduced.

2. <u>Airbag deployment phase.</u> In this phase the airbags are inflated and the occupants tighten the belts while moving forwards with a relative velocity with respect to the car. This relative velocity should be sufficient low, because in practice many injuries are the result of reaching a still inflating airbag or hitting a full inflated bag with a relative high velocity. The deceleration should be low.

3. <u>Occupant contact phase.</u> In this phase, the occupants have hit the airbags and there is stiff contact between the occupant and the car. High decelerations may occur because the occupants will not be subjected to further shock loads caused by contact with the interior, deceleration should be substantially in the remaining time.

The optimal deceleration pulse for this realistic interior at a crash speed of 56 km/h into a rigid full-width barrier is given in figure 1, figure 2 illustrates the pulse of a normal realistic deceleration.

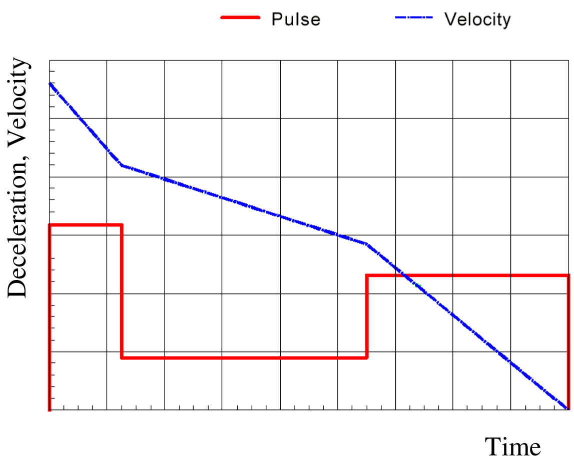


Figure 1. Optimal deceleration pulse.

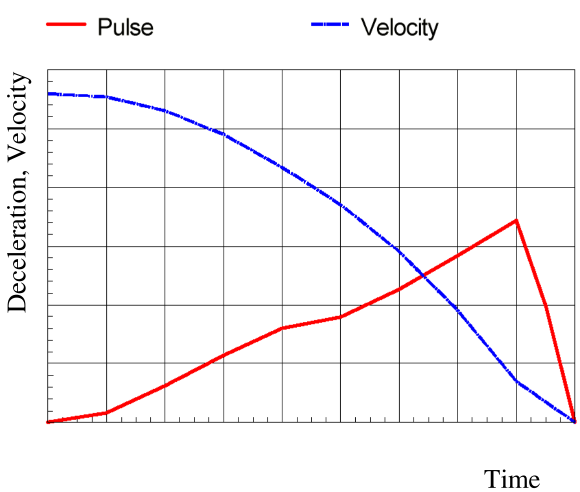


Figure 2. Deceleration pulse of nowadays cars.

From this research [3] it is concluded that the OSI of the optimal crash pulse, at this velocity, is 35 per cent lower than the OSI of realistic pulses. As an example optimal pulses for 3 different velocities are shown in figure 3. For design reasons it is plotted as function of the deformation length.

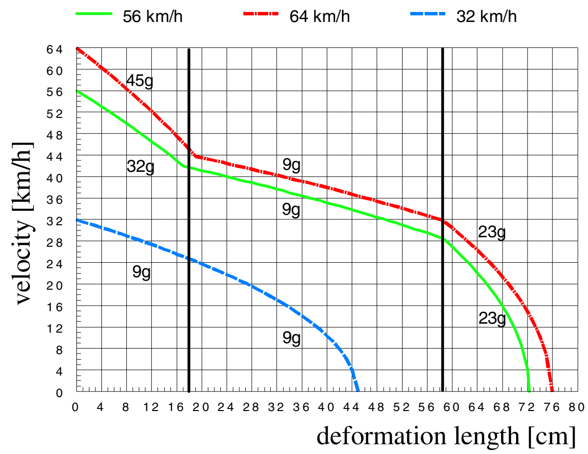


Figure 3. Three optimal decelerations curves in three phases [3].

This high-low-high pulse shape can also be found with the application of Newton's second law for motion in the x-direction while modeling the mechanical relationship among the occupant, vehicle and seat belts as shown in figure 4. Consider the occupant as a point mass with a mass of m and the vehicle as a point mass with a mass of M, and the seatbelt as a linear spring with coefficient of k.

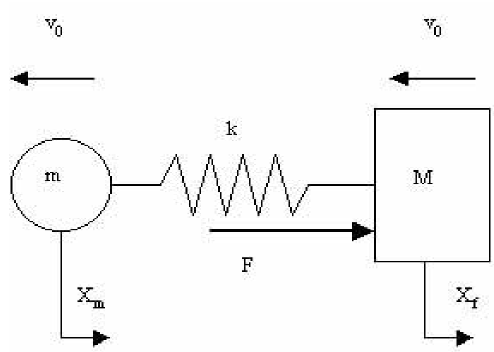


Figure 4. Two mass, one dimensional model.

The moment at the start of the crash is the origin for the time axis (t=0). v_0 is the initial velocity of each point mass, and the co-ordinates for each point mass are X_m and X_f (see figure 4), which are respectively measured from the position of each at the start of the crash. F is the crash load acting on the vehicle point mass. The equations of motion can be expressed by equation 1,

$$M\ddot{X}_f = k(X_m - X_f) + F \qquad (1).$$

This gives as result that for a constant deceleration (C) of the vehicle the deceleration of the occupant is described by figure 5.

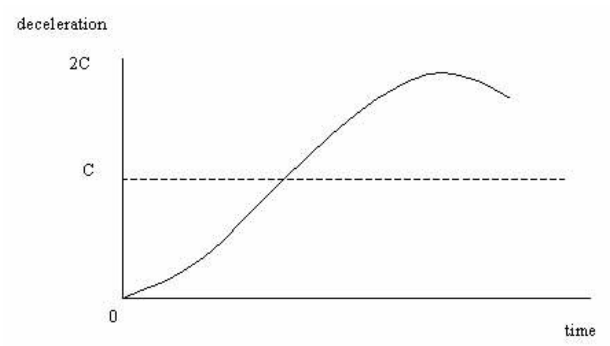


Figure 5. Typical occupant deceleration model for conventional vehicle.

In order to smooth the peak in figure 5, the deceleration of the vehicle has to be altered and can no longer be constant. The mathematical solution gives a cosine type equation for the vehicle deceleration that leads to a smaller and smoother pulse for the occupant; both can be seen in figure 6.

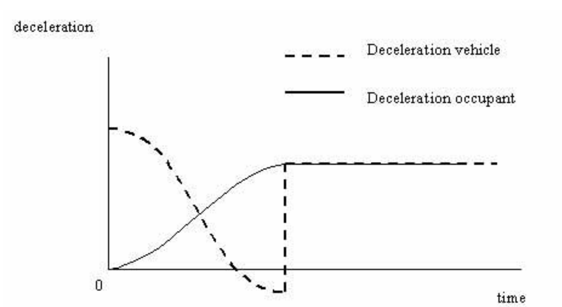


Figure 6. Deceleration of vehicle and occupant.

In the above figure it is seen that the vehicle deceleration pulse can be divided in to three phases; high, low and moderate level. This result is unanimous to the research described earlier [3]. Motazawa and Kamei [4] conclude the same.

Regarding the feasibility of the "high-low-high" crash pulses, there is one major difficulty that a vehicle structure will always start buckling or bending at its weakest point. This means that even if the front structure is stronger in its most forward parts, but weaker in parts closer to the firewall, the weaker part will always buckle first. Thus a pulse with an initial deceleration peak can almost only be created by inertial effects or by actively controlling the stiffness of the energy absorbing members during deformation. A nice example of a fixed structural element is from Motazawa and Kamei [4]. They have designed a structural concept that is able to create a fixed high-low-high pulse. The fundamental model (see figure 7) is a hollow member designed to act as a longitudinal. It consists of a front zone for axial collapse, and a center zone for bending. The axial collapse zone incorporates a stress concentration in order to induce regular buckling deformation, while the bending zone has a mildly cranked shape to stabilize the bending deformation direction. Each of the cross-sections is set so that the deformation load of the axial collapse zone will be slightly less than the maximum load of the bending zone.

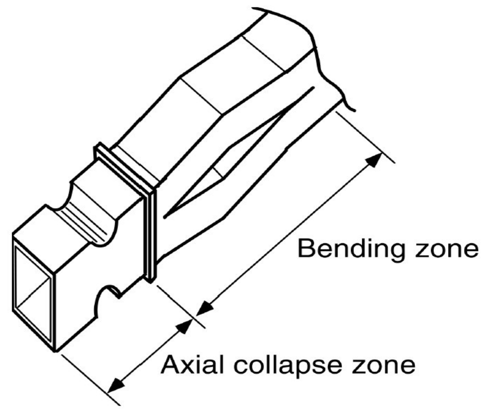


Figure 7. Fundamental model of a crash load control structure [4].

However, if this fundamental model is applied in an actual vehicle body, in a low speed crash, there is a possibility that the initial stage would not be completed and a large crash load is maintained until the vehicle stops.

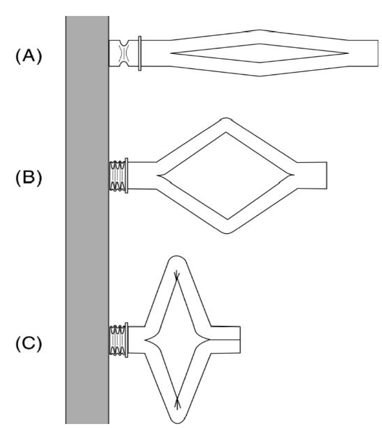
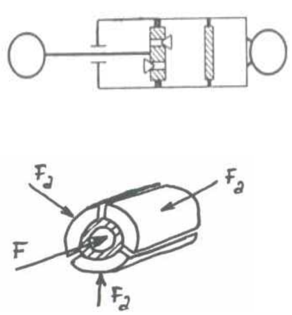


Figure 8. Deformation process in the fundamental model [4].

Figure 8 illustrates the deformation process for this fundamental model. The A-section in the figure shows the first stage, during which the axial collapse zone starts to deform immediately after the start of the crash due to its inherent stress concentration. After the axial collapse zone has started to deform a nearly constant load is maintained. When the regular buckling deformation has proceeded through the length of the axial collapse zone, the load increases and eventually reaches the maximum load for the bending zone. Figure 8B illustrates the second stage. When the maximum bending load is exceeded, the bending zone rapidly deforms, and the load drops to a fraction of its former level. Figure 8C illustrates the third and final stage after the bending deformation is completed. The load again starts to increase as the deformable members bottom out.

ADAPTABLE ENERGY ABSORPTION BY FRICTION

To design a structure from which the energy absorption can be varied depending on the crash situation, a traditional structure with crumpling beams with a fixed force level is not usable. Therefore alternative ways of energy absorption which can be influenced must be searched for. In figure 9 two interesting principles for frontal crash application are showed. One possible solution is a hydraulic system (figure 9a), two cylinders (placed along or instead of the two longitudinal members) with controllable flow restriction valves could control the oil flow and therefore the force level required to move the pistons backwards during a frontal crash. These idea is also used by Witteman [6] and Jawad [7]. Disadvantage could be the weight and space requirements for automotive.



a

b

Figure 9. Examples of energy absorption by a hydraulic cylinder with variable restriction (a) or by axial friction (b).

The other practical method to absorb kinetic energy is by means of friction (figure 9b). Changing the pressure force on a friction block regulates the energy absorption. The well functioning idea of hydraulic vehicle brakes can be used during a crash on very stiff longitudinal beams moving backwards, which must be positioned in such a way that the profiles move under the vehicle floor.

To determine the necessary friction force, the velocity information of the vehicle must be used. Since most modern cars use ABS which continuously detects the speed of each wheel, the current speed (or before the last 100 ms from memory to prevent crash influence) of the car is always well known.

In a new designed front-end structure that can adapt its frontal stiffness during a crash, the crushable longitudinals have been replaced by (plastically) undeformable U-profiles, see figure 10. The beams have not to crumple to absorb energy so they can be made very stiff with a high bending resistance yielding no risk for a premature bending collapse in case of an oblique crash direction. In a crash the profiles are forced backwards and slide each along two active friction pads (supported by two break cylinders) absorbing the energy, the friction pressure can be hydraulically altered leading to variable stiffness. It is calculated that for a 1100 kg vehicle the pressure for the brake pads has to vary between 5 and 25 bar. The temperature increase after a 64 km/h crash is only about 85 degrees for the pads and the profiles. This designed structure makes it possible to decelerate a car as described in figure 1. For the regulation process servo valves are available for the required pressure and volume flows, which can regulate within a few milliseconds, see figure 12 for the hydraulic circuit. In a crash the slant profiles slide under the occupant compartment or, in case of a Multi Purpose Vehicle, in the floor compartment without jamming the occupants. The system is equipped with a cable connection system, as designed by Witteman [8]. If only one side of the vehicle front is loaded (offset or oblique crash), the backwards moving profile takes the mounted cable that is guided along two cable guide disks to the other side also backwards. This cable generates a tensile force on the other profile which pulls that profile also backwards, yielding a symmetric force distribution. The designed structure is able to involve the whole frontal structure into an energy dissipation process, even in an offset crash. See figure 11. Because both profiles always slide together backwards, the same crash behavior is shown for the whole frontal part with the engine and other aggregates for each frontal crash position and a stiff bumper part can be mounted in front for a very high bending resistance of the whole frame and for a better car to car interaction.

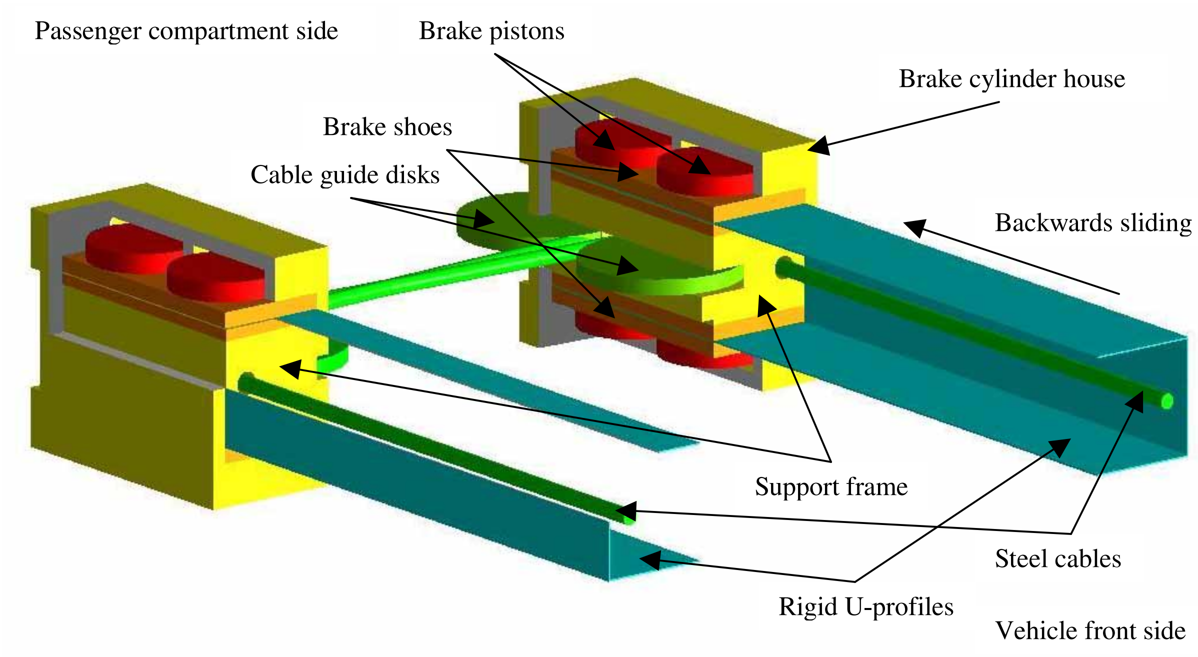


Figure 10. Open view of frontal structure with cable and brake system.

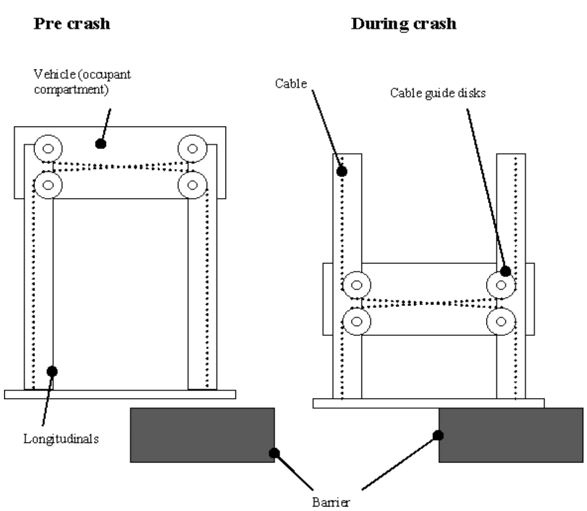


Figure 11. Frontal structure with cable system to involve the not directly loaded beam in an offset crash.

With this structure the car is able to adapt its frontal stiffness, depending on the crash velocity. The maximum length of the crumple zone can always be used, without intrusion of the occupant compartment. Of course the packaging of the engine and other stiff aggregates influence the available deformation length. High crash loads from these parts can be compensated by less friction force on the profiles. Now the front-end is *'as soft as possible, as hard as necessary'*.

An optimal regulation for the whole deformation length is of course with a computer controlled system, which measures continuously the actual deceleration level and adjusts at the same time the pressure for the friction pads to reach the programmed optimal deceleration pulse. In this way, it is also possible to compensate for the stiffness, velocity or weight of the colliding obstacle. This would be an ideal solution for the compatibility problem between small and large vehicles.

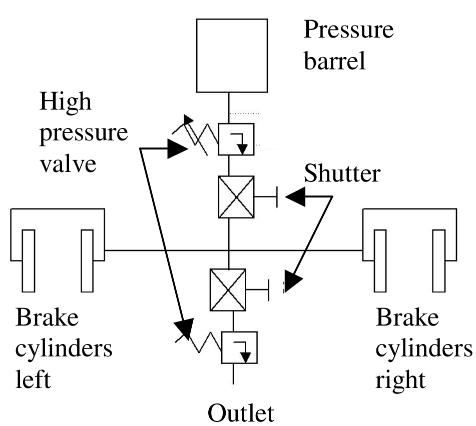


Figure 12. Schematic view of hydraulic regulation circuit.

CONCLUSIONS

With the presented new frontal structure design the amount of absorbed energy for each crash situation (full, offset, oblique, high or low speed) can be adapted to fully utilize the available deformation length with an optimal deceleration curve without deforming the passenger compartment yielding the lowest injury values. This intelligent structure with adaptable stiffness based on very fast adjustable friction forces before and during the crash is also a solution for the compatibility problem between different vehicle masses and stiffnesses or for compensating the measured additional occupant and luggage masses.

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